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N. N. Martovetsky, P. Bruzzone, B. Stepanov, R. Wesche, C. Gung, J. V. Minervini, M. Takayasu, L. F. Goodrich, J. W. Ekin, A. Nijhuis

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Effect of the conduit material on CICC performance under high cycling loads

Nicolai N. Martovetsky, Pierluigi Bruzzone, Boris Stepanov, Rainer Wesche, Chen-yu Gung, Joseph V. Minervini, Makoto Takayasu, Loren F. Goodrich, Jack W. Ekin, Arend Nijhuis

***Abstract*— Recent ITER Model Coils and CRPP tests on Nb3Sn Cable in Conduit Conductors (CICC) showed a significant and unexpected increase in the broadness of the transition to the normal state, resulting in degradation of superconducting properties. To investigate these phenomena two CICC samples were built with identical 144 strand cables but different conduit materials. One sample had titanium conduit with low coefficient of thermal expansion (CTE), the other had stainless steel conduit. The purpose of this experiment was to study changes in strand properties in the cable (n-value, I_c, T_{cs}), the effect of cycling and high electromagnetic load and the effect of the conduit on the CICC performance.**

***Index Terms*—Superconducting cables, superconducting filaments and wires, Nb3Sn cable in conduit.**

I. Introduction

It is well known that the Nb3Sn critical current is sensitive to strain and therefore to the conduit material CTE. Degradation of the superconducting properties observed in ITER Model Coils test results [1-3] extended our knowledge base about Nb_3Sn CICC and required significant conductor design changes in order to meet ITER requirements. Many questions about Nb_3Sn CICC behavior with high currents still remain without satisfactory explanation. In the Model Coils it was observed that all tested Nb_3Sn CICC performed below expectations as estimated by the mismatch between coefficients of thermal expansion (CTE) for the conduit and the strands. Especially surprising was lower than expected performance of the CICC in low CTE conduits (Incoloy and Ti), which were expected not to degrade the superconducting cable noticeably. The TFMC [3], the only stainless steel (SS) CICC in this R&D, also showed somewhat more degradation than expected.

Model Coils also showed that cyclic loads could cause yet more degradation of properties. One low CTE CICC had significant degradation (about 0.5 K) [1], and another one about 0.15 K [4]. The remaining low CTE [2] and SS CICC [3] had cyclic degradation less than barely detectable 0.1 K.

The CICC design and analysis in ITER and many other projects are based on the correlation of Nb_3Sn performance by Summers-Ekin [5] based on strain data above –(0.3-0.4%) and extrapolated to higher compressive strain when necessary. The data obtained recently by University of Durham group [6] on Nb_3Sn strands under higher uniaxial compression suggest that the Summers relation is too optimistic for highly compressed Nb_3Sn. This now introduces confusion about prediction of the CICC properties on the basis of the strand properties, since the Durham correlation has a narrow range of validity and Summers correlation was used for the analysis and interpretation of the CSMC and most Nb_3Sn conductors since 1991, including highly compressed CICC with SS conduits.

The Model Coil data had limited accuracy since there was noticeable scatter in the properties of the strands used. Also, due to a very large magnet and difficult access, it was not always possible to place the instrumentation in the best locations. Also it was not possible to know if handling the conductor during fabrication after the heat treatment (HT) caused any degradation.

The objective of the experiment discussed in this paper was to study the transformation of the Nb3Sn strand properties in CICC based on accurate knowledge of the initial strand properties and to compare behavior of CICC in steel and low CTE conduits undisturbed by coil fabrication operations after HT. Two identical cables made from the excess IGC strand used for the CS Model Coil were encapsulated into two tubes: 304 type stainless steel and pure Ti conduits. We bent the CICC into hairpin samples and heat-treated them. We instrumented the samples with voltage taps and temperature sensors and tested the samples in fields up to 11 T in the SULTAN facility at CRPP, Switzerland. To eliminate the current redistribution problems, the cable terminations were stripped of Cr plating and filled with SnAg solder. The conductors layout is given in Table I.

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Author N.M. is with Lawrence Livermore National Laboratory, Livermore, CA 94550 USA (telephone: (925) 422 4269, e-mail: martovetsky1@llnl.gov)

P.B., B.S., R.W. are with the Centre de Recherches en Physique des Plasmas, CH-5232 Villigen-PSI, Switzerland (e-mail: pierluigi.bruzzone@psi.ch)

C.G., J.V.M. and M.T. are with MIT Plasma Science and Fusion Center, Cambridge MA 02139, USA (e-mail: minervini@psfc.mit.edu)

L.F.G. and J.W.E. are with the National Institute of Standards and Technology, Boulder, CO, 80305 USA (e-mail: goodrich@boulder.nist.gov)

A.N. is with University of Twente 7500 AE Enschede, the Netherlands (e-mail: a.nijhuis@tn.utwente.nl)

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TABLE I
TESTED CICC PARAMETERS

	SS	TI
Nb_3Sn strand Diameter	0.81 mm	
Cu:non-Cu	1.5 ± 0.05	
Cr plating	2 μm	
Cable configuration	3 x 3 x 4 x 4 = 144	
Cable pitches	10 / 51 / 79 / 136 / 166 mm right hand	
Void fraction	≈ 33.1 %	
CICC diameter, mm	14.51 – 14.57	14.56 – 14.59
Jacket material	Stainless steel 12X18H110T	Ti (grade 2)

II. STRAND CHARACTERIZATION

The strand properties were measured in several laboratories: NIST, MIT, CRPP and University of Twente (UT). UT measured strain effect at two temperatures, work is still in progress, the NIST and CRPP had variable temperature capability, while all MIT data were taken at 4.2 K. The scatter among the NIST, UT and CRPP data without applied strain was small; MIT data were 2-3% lower. The strand properties without applied strand can be satisfactory described by the Summers correlation [5] with the following parameters: Co=11776 AT/mm^2, T_{c0m}=16.8 K, B_{c2m}=28.5 T, assuming resulting stress of –0.25%. The strain sensitivity was measured at NIST on an identical strand which underwent slightly different heat treatment resulting in 11% higher I_c (12 T, 4.2K, 10 μV/m). Reduced by 11% I_c data are showed in Fig. 1 along with the Summers correlation.

III. CICC WITH SS CONDUIT

The test procedure for the samples was as follows.

After calibration runs and checks and AC tests with no transport current, the Tc0m measurements were attempted but were not very successful due to hydraulic instabilities above 15 K. The I_c was then measured in the background field. We started at the lowest IxB force at 11 T and 8 K to find out if first cycle of electromagnetic loading is important in the degradation evolution. The critical current I_c and current

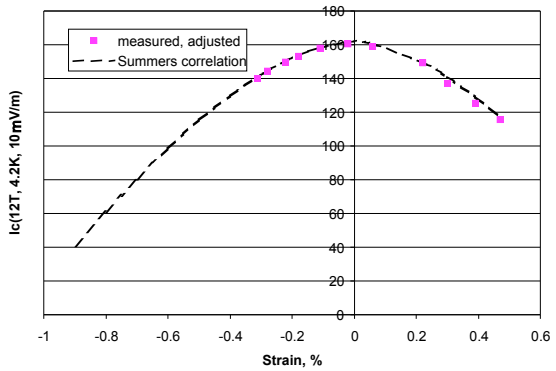

Fig. 1. Strain sensitivity of the IGC strand at 12 T and 4.2 K.

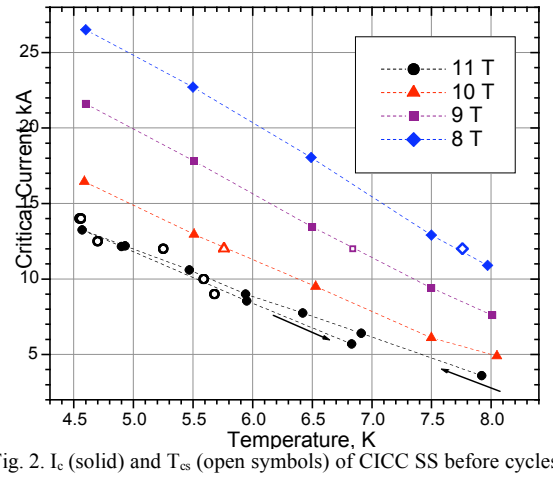

Fig. 2. I_c (solid) and T_{cs} (open symbols) of CICC SS before cycles.

sharing temperature T_{cs} were measured at 10 μV/m over 30 cm in the high field length. All data are taken at 3 g/s flow rate through each leg. Test results on the SS sample before cycling are shown in Fig.2. The arrows for 11 T measurements indicate the sequence of I_c measurements. It is seen that after exposing the CICC to the highest IxB the I_c noticeably decreased, which shows that the very first loading affects the strand properties.

After cycling from 0 to 17 kA at 10 T and 4.5 K, the properties of the CICC degraded in a more continuous manner. The I_c of the SS sample came to saturation after about 600 cycles as shown in Fig. 3. The nomenclature b.c. corresponds to "before cycles" and a.c. to "after cycles". The I_c dropped by 10-20% (higher in higher field) and in terms of T_{cs} – by about 0.5 K at 11 T – about the same amount as the ITER CS Insert and with a similar amount of cycles to saturation. Similar to this work, samples measured at SULTAN in the year 2001 [8] had the I_c saturated after about 2500 cycles, but the I_c degradation was about 20% there.

IV. CICC WITH TI CONDUIT

The CICC with Ti conduit tests were conducted similar to the CICC with SS conduit. The Ti conduit sample had higher initial I_c and I_q, as expected. The degradation of current as a result of cycling was similar to the SS CICC.

Fig. 4 shows comparative degradation of the CICCs

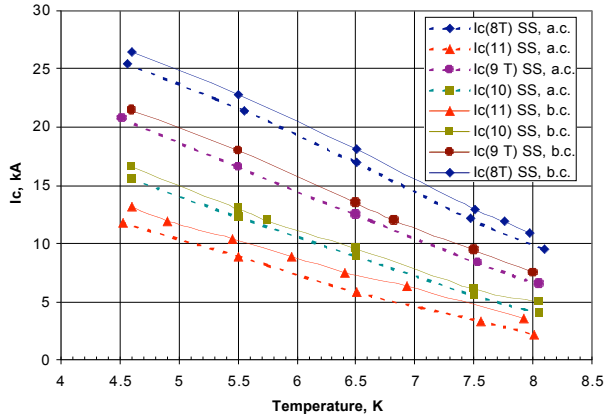

Fig. 3. Ic (10 μV/m) in the SS CICC before and after cycles.

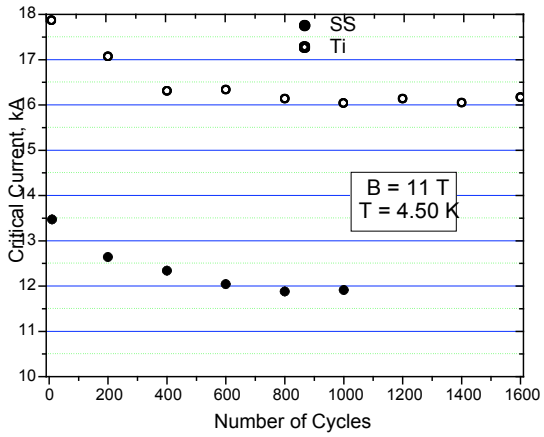

Fig. 4. Evolution of Ic as a result of load cycles

studied. The ratio between I_c (Ti) and I_c (SS) versus cycles at 11 T and 4.5 K always was in the range of 1.32-1.36.

In agreement with earlier results reported in [8], the quench current I_q (thermal run away) changed much less than I_c due to cycles. Fig. 5 shows comparison of I_q for both CICCs. The quench current depends on the helium mass flow and length of the conductor in the peak field [9], therefore it reflects not only the superconducting properties, like I_c, but also operating conditions. Both I_c and I_q of the low CTE Ti conduit show about 30% advantage over the SS conduit at 11 T and 4.5 K. At 12 kA and 11 T the Ti CICC has Tcs by 1.3 K higher than the SS CICC. This result is consistent with the ITER Model Coil results [4] where similar performance strands (Furukawa and LMI) had about 25-30% advantage in Incoloy 908 conduit (CS Insert) versus SS conduit and structure (TFMC). The advantage is lower than the expected 50-60% before Model Coil program.

Such a small difference in I_q at noticeable reduction of I_c as a result of the cyclic load can be explained by a reduction of the n-value of the resistive transition, expressed as $E=(10^{-5})*(I/I_c)^n$ [V/m], where I_c is defined at the level of 10^{-5} V/m.
Fig. 6 shows a summary of the n-value for the original strands

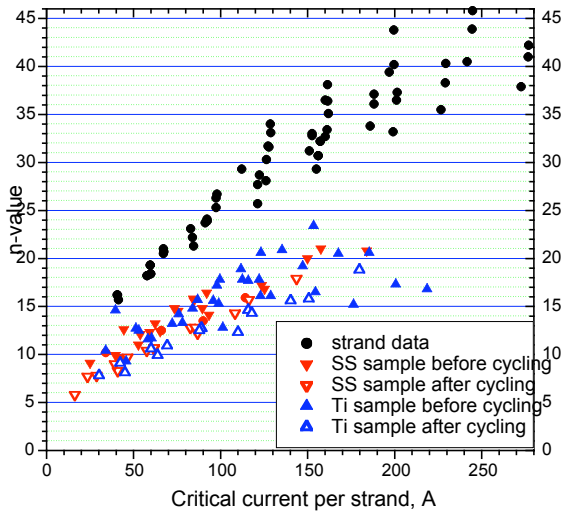

Fig. 6. Summary of the n-value measurements

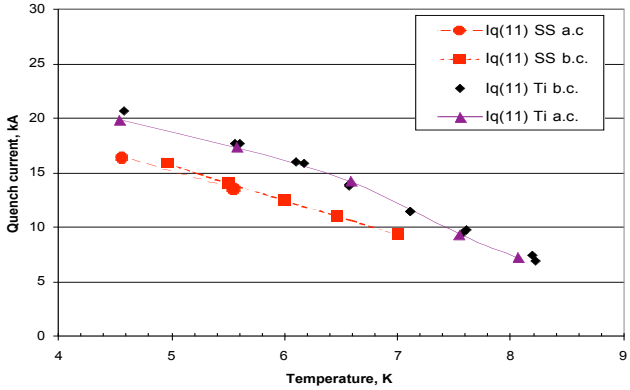

Fig. 5. Quench current in CICC at 11 T before and after the cycles. The lines are to guide the eye.

and for both CICCs. As in the ITER Model Coils, the n-value for CICC is significantly lower than that in the stand-alone strand, including the data before loading and at minimal IxB values. That suggests that the degradation in the strands at least partially comes from heat treatment in a conduit and following cooldown. Quantitatively, the n-value for low CTE conduits tested at Model Coils (about 8 at 40 A/strand) [1] is similar to values observed in our tests, while the n-value measured in the TFMC (about 7 at 111 A/strand) is significantly lower than what we measured for SS CICC. It is unexpected to see that the low CTE conduit did not produce higher n-values in the cable than in the SS conduit. Strand data [6,7] on I_c versus strain always showed a higher I_c associated with a higher n-value.

V. Post Test Analysis and Discussion

We assume that the current is uniformly distributed over the cable, which is confirmed by negligible voltage measured across the cross section. Thus, the CICC transition represents purely strand behavior, not current transfer between the strands. To compare performance of the strand with CICC, we need to take into account that the strand in CICC is located in a variable field due to self-fields produced by the transport current and cabling. We used a double spiral to model the four-stage cable, modeling only the two most important last cabling stages, and calculated the electrical field along the length of the strand. The integrated electrical field should be compared to the measured electrical field. For the sake of analysis, the varying magnetic field along the length of the strand between the voltage taps is replaced with a single value of the "effective magnetic field", which is found to fit the integrated electrical field along the strand. This effective magnetic field, Beff, depends on the n-value. For an n-value of 10, Beff is approximately equal to the median magnetic field between the peak and average in the cable cross section. That is Beff=(Bpeak+Baverage)/2 = Bsultan+kI, where coefficient k is computed to be 0.02 T/kA and I is the transport current. At the highest transport currents of 30 kA, the effective magnetic self-field is calculated as 0.6T and peak electrical field is about 4 times higher than the measured average electrical field.

The anticipated strain of the Nb3Sn strands in the SS

conduits after cooldown is somewhere within –0.55-0.75%. For the Ti CICC we anticipated about –0.2-0.3%.

Although there are doubts that the Summers correlation is accurate for high compressive strains, we will assess the CICC performance using the Summers correlation in the full range of the strain, since we do not have reliable data and correlation for high compressive strain yet. This approach may mean that the strain deduced from the test data may be merely a fitting parameter rather than a real strain in the strands. But even such reservation makes analysis valuable for comparison with the Model Coils results. Also, the model can be used for CICC design if operating conditions are not far away from the test conditions.

In the Model Coil analysis, the Summers correlation was used to compare the performance of the strand in CICC and stand-alone strand. It was found [3, 10] that this correlation can describe the parameters of the CICC if a fitting parameter is introduced in the form of an extra strain in addition to cool down and operating hoop strain (hoop strain is zero in our test): $\varepsilon = \varepsilon_{cd} + \varepsilon_{op} + \varepsilon_{extra}$. This additional strain is assumed as $\varepsilon_{extra} = aIB$ that takes into account the transverse force crushing and bending the strands in the cable in lateral direction; this is just a common sense speculation. Using this approach we found the best fit to describe the test data and results by the Summers correlation.

The fitting process results are given in Table II in terms of cooldown strain and coefficient for the extra strain. Some analysis data from the Model Coil program are shown for comparison, which indicate that a low CTE conduit is a superior material for Nb3Sn CICC to the SS. The advantage, however, is less than expected from I_c versus uniaxial strain data.

TABLE II
FITTING PARAMETERS FOR THE STRAIN IN CICC

	$\varepsilon_{cd\%}$	a [1/□□□]
Ti CICC b.c.	-0.458	-4.20e-6
Ti CICC a.c.	-0.539	-2.65e-6
SS CICC b.c	-0.600	-6.91e-6
SS CICC a.c.	-0.683	-3.75e-6
Ti TFI in SS structure [11]	-0.575	-2.58e-6
SS TFMC [3,10]	-0.66	-2.3e-6
Incoloy CSI [10] b.c.	-0.32	-3.5e-6
Incoloy CSI b.c. [12]	-0.45	n/a
Incoloy CSI a.c. [12]	-0.56	n/a

VI. CONCLUSION

Low CTE conduit maintains its significant advantage in I_c and I_q over the SS conduit in all tested conditions. Both CICCs experience about 10% degradation in I_c due to cycling, suggesting that the effect of cycling on I_c is insensitive to the conduit material.

Even with careful handling after heat treatment, the degradation in I_c for the CICC with low CTE is comparable to the degradation seen in CSMC, CS and TF inserts. We see degradation even before high electromagnetic loads are applied. Thus, low CTE conduits do not completely eliminate I_c degradation and that suggests that the CICCs in Model Coil program were not damaged during fabrication.

The n-value in the low CTE conduit CICC is only slightly higher than in the SS conduit; both are a little more than one half that of the original strand, which is unexpected and yet to be explained.

The subscale tests reproduced many Model Coil program results and gave valuable data for CICC design database.

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